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Deterministic Scheduling Algorithm Based on Proportional Conflict and Deadline in Industrial Wireless Networks

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Abstract. Deterministic scheduling technology is of great significance for the real-time and deterministic transmission of industrial wireless network data. In view of the fact that the industrial wireless network data stream itself has priority classification attribute, this paper, based on multi-channel time-division multiple access (TDMA) technology, analyzes link conflict delay and channel contention delay caused by high priority data stream to low priority data stream, and performs scheduling preprocessing on the network, so as to eliminate the network with unreasonable parameters, and feedback to the network manager. For preprocessed networks, the scheduling algorithm prioritizes the allocation of time slots and channel resources for links of high priority data streams, while for data streams belonging to the same priority class, a scheduling scheme based on Maximum Proportional Conflict and Deadline First (MPC-D) is proposed. Under the premise of meeting schedulability conditions, time slots and channel resources are allocated sequentially according to the proportional conflict deadline values of each link, from largest to smallest. The experimental results show that the proposed scheduling algorithm can achieve a high network scheduling success rate.

Keywords: industrial wireless network, deterministic scheduling, scheduling preprocessing, link conflicts

1 Introduction

1.1 Research Content and Main Work

As one of the important components of industrial communication systems, industrial wireless networks will reduce the use of factory cables and save a lot of costs compared to traditional wired networks. Meanwhile, the use of wireless communication technology will make the deployment of equipment more flexible, which is an important component of future factory upgrades and smart factory construction [1-4]. Industrial wireless standards mainly include WirelessHART standard [5], ISA100.11a standard [6], and China's independently developed WIA-PA standard [7]. Ensuring that data is transmitted within the deadline is particularly important in industrial wireless networks, and deterministic scheduling technology can effectively solve the problem of periodic data flows under deadline constraints. Industrial wireless standards usually support TDMA technology at data link layer [8], and use multi band communication at physical layer, providing slot resources and channel resources for deterministic scheduling. Deterministic scheduling can meet the deterministic requirements of data transmission by reasonably allocating determined communication resources to the data flow link.

1.2 Research Status at Home and Abroad

At present, the deterministic scheduling problem in industrial wireless networks has been proven to be an NP-hard problem [9]. There is currently no unified solution method for this type of problem. According to different characteristics of solution strategy, it can be divided into traversal search algorithm, graph coloring algorithm, priority algorithm, and heuristic algorithm. Literature [9] proposed an optimized Branch and bound scheduling algorithm for the deterministic scheduling problem in Wireless HART networks. The algorithm reasonably de-

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signed the judgment conditions in the search process to optimize the traversal process, and improved the search efficiency. Reference [10] proposed a graph coloring scheduling algorithm based on TDMA mechanism, which adopts distributed graph coloring and considers the clustering characteristics of the network.

Research on deterministic scheduling problems has also made certain progress in various industrial wireless networks. For example, for the WirelessHART network, Saifullah et al. proposed the C-LLF scheduling algorithm [9]. This algorithm designs resource allocation for data flow links by jointly considering the minimum free time of the data flow link and the degree of link conflict in the subsequent scheduling process. The C-LLF algorithm considers the situation of multiple channels, but does not consider the inherent priority attribute of the data flow. Reference [11, 13] also analyzed the latency of end-to-end data streams in fixed priority networks around WirelessHART networks, but did not provide a specific scheduling method for data streams with fixed priority. In summary, the above research literature on the scheduling problem of industrial wireless networks either does not consider the presence of multiple channels in industrial wireless networks, or does not consider the inherent priority attributes of data flows in the network. In addition, there are few studies on the presence of multiple data streams under the same priority.

In industrial wireless networks, data streams themselves have priority attributes, and their priority is determined based on the characteristics of business applications. For example, the WIA-PA standard specifies four data priorities [12], arranged in descending order: non-emergency alarm data, general data, process data used for industrial automation production monitoring, and command frames for processing network management control and emergency alarms. When there are multiple data streams with the same priority in the network, the deterministic scheduling problem needs to consider the allocation of time slots and channel resources to meet the delay constraints of all data streams. On this basis, it is necessary to ensure the priority allocation of time slots and channels for high priority data streams as much as possible.

1.3 Research Content and Main Work

Therefore, for the data stream with priority classification attribute under the multi-channel TDMA mechanism, this paper analyzes the delay caused by the high priority data stream to the low priority data stream in the worst case, and uses the delay analysis results to schedule the network, so as to eliminate some networks with unreasonable parameters, and feedback to the network manager for processing. For pre-processed networks, when allocating time slots and channels, priority should be given to the links of high priority data streams; A scheduling scheme based on Maximum proportional conflict and deadline first is proposed for links with the same priority, and each link is scheduled sequentially from large to small according to this value. The simulation results validate the correctness of the proposed scheduling scheme and indicate that it has a higher scheduling success rate compared to classical priority scheduling methods.

2 Network Model and of Scheduling Problem

2.1 Network Model

Industrial wireless network can be modeled as a graph $G = (N, V)$, where N is a set of nodes in the network that constitute the vertices of the graph. V represents the communication links between nodes in the network, forming the edges of the graph. For two nodes N_a and N_b in the network, if they can communicate with each other, they can form a bidirectional communication link $(N_a, N_b) \in S$. At the same time, this article only considers the situation where the network node is a single antenna device, and the node cannot simultaneously perform transmitting and receiving actions. For the links to be scheduled in the same time slot $\overrightarrow{N_a N_b}$ and $\overrightarrow{N_x N_y}$, if $(N_a = N_x) \vee (N_a = N_y) \vee (N_b = N_x) \vee (N_b = N_y)$ are true, then the two links will have transmission conflicts and cannot be scheduled in the same time slot.

2.2 Data Flow Models and Assumption

Fig. 1 is a schematic diagram of a data flow in an industrial wireless network. The source node periodically generates data, which passes through the routing and gateway forwarding connected by the thick dashed line in the figure and enters the destination node D, forming a periodic end-to-end data flow. The destination node of end-to-end data flow can also only go to the gateway, and there are multiple end-to-end data flows in the network.

Assuming that there are end-to-end data streams in the network, represented by $F = \{F_1, F_2, \ldots, F_n\}$, and the data stream $F_i \in F$ periodically generates data with a period of T_i, and there are k types of different priorities $P = \{P_1, P_2, \ldots, P_k\}$. A smaller P indicates a higher priority, and the data streams contained within it are relatively more important, and each type of priority can contain more than one end-to-end data stream, but a data stream can only have one priority level. In this article, $hp(F_i)$ represents the set of all data streams with priority categories higher than F_i .

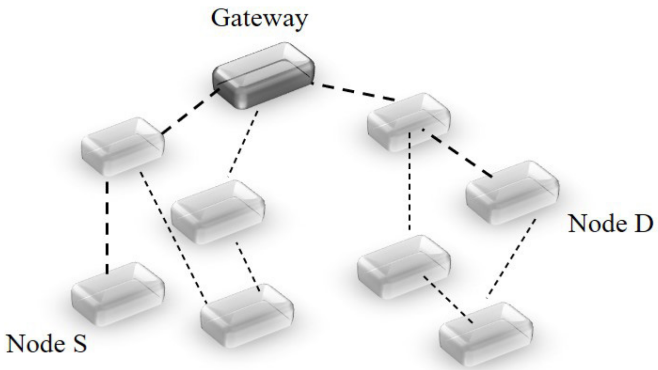

Fig. 1. Illustration of data flow in industrial wireless network

In deterministic scheduling based on time slots, E_i represents the relative deadline time slot size for data flow F_i to complete an end-to-end transmission, H_i represents the number of routing hops on the end-to-end path of data flow F_i, that is, the number of links contained in its end-to-end transmission path, and L_i represents the actual number of time slots for data flow F_i to complete an end-to-end transmission. If the source node of data stream F_i generates data in time slot m and reaches the destination node in time slot n, the end-to-end transmission delay of data stream F_i is:

$$L_i = n - m + 1. \tag{1}$$

Let D_i represent the total delay in time slots caused by all high priority data streams to the data stream , which is the delay caused by $hp(F_i)$ high priority data streams. When scheduling, the data stream F_i must complete the transmission within the deadline time slot E_i, so it needs to meet the conditions:

$$L_i = D_i + H_i \le E_i. \tag{2}$$

2.3 Mathematical Description of Deterministic Scheduling

The scheduling goal of industrial wireless networks is to ensure that the time slot for any data flow in the network to reach the destination node is less than its absolute deadline time slot, which can be expressed as:

$$L_i \le C_i, \forall i \in [1, N]. \tag{3}$$

Because every node in industrial wireless networks uses half duplex communication, it requires that one node cannot simultaneously transmit and receive data at each time slot. Let $I\ (N_a)$ represent the set of links where all data flows in the network enter node N_a, and $O(N_a)$ represent the set of links where all data flows in the network leave node N_a. When in time slot t, the directed communication link between node N_a and node N_b $\overrightarrow{N_a N_b}$ is represented as $S_t(N_a, N_b)$. If node N_a sends data to node N_b once in time slot t, then $S_t(N_a, N_b) = 1$. If no data is sent, then $S_t(N_a, N_b) = 0$. So the constraint can be expressed as:

$$\begin{aligned}&S_t(N_a, N_b) \in \{0,1\}, S_t(N_b, N_a) \in \{0,1\} \\ &\forall N_a \in N, \forall N_b \in N.\end{aligned} \tag{4}$$

$$\begin{aligned}&\sum_{(N_a,N_b)\in I(N_a)} S_t(N_a, N_b) + \sum_{(N_a,N_b)\in O(N_a)} S_t(N_a, N_b) < 1, \\ &\forall N_a \in N, \forall N_b \in N.\end{aligned} \tag{5}$$

3 Data Flow Scheduling Preprocessing and Algorithm Design

3.1 Data Flow Scheduling Preprocessing

When conducting deterministic scheduling on the network, there may be some data flows with unreasonable parameters in the network that needs to be scheduled. By analyzing the delay of the data flows in the network and further combining the deadline requirements of each data flow, scheduling preprocessing can be carried out on the required scheduling network to eliminate some networks with unreasonable parameters, thereby reducing the complexity of the entire scheduling process algorithm. This article adopts a delay analysis method suitable for industrial wireless networks to analyze the delay of end-to-end data streams under different priorities [11].

Due to the limitations of half duplex antennas and limited communication resources in the network, each hop link of the data stream will experience two types of delays during transmission: link collision delay and channel competition delay. In the same time slot, when link conflicts occur between links of different priority data streams, multiple links transmit containing the same node. At this time, regardless of how many available channels are included in the network resources, the links of lower priority data streams will be affected by delay. In this article, without considering the spatial reuse of channels, the channels in network communication resources can be analogized to processors in multiprocessor systems, and the data flow in the network can be analogized to a task that needs to be executed in multiprocessor systems. Furthermore, the data flow channel competition delay can be analogized to multiprocessor scheduling delay, and existing multiprocessor scheduling results can be used to analyze channel competition delay.

On the basis of analyzing the delay of the data stream, scheduling preprocessing combines the deadline constraints of the data stream itself to determine the required scheduling network, filter out some networks with already very low scheduling success rates, and thus achieve the effect of excluding networks with unreasonable parameters. Specifically, starting from the lowest priority, traversing all data streams of the current priority, using the data stream delay analysis method [11] to calculate the total delay D_i caused by all higher priority data streams on the current priority data stream F_i. Combined with the minimum transmission time slot required for the data stream itself to complete transmission, the end-to-end transmission time slot $L_i = D_i + H_i$ of the current class data stream F_i affected by the higher priority data stream delay can be obtained. By calculating the L_i value of each data stream of each type of priority, the maximum end-to-end Transmission delay of each data stream affected by the higher priority data stream is obtained. Compared with its own deadline C_i, if L_i is greater than C_i, the data stream is not schedulable in the worst case, and the network is no longer scheduled for communication resources. By traversing all data flows in the network, if the maximum end-to-end Transmission delay of all data flows is less than or equal to their respective deadline, the current network is considered to be schedulable in the worst case.

3.2 Algorithm Design

The data flows in the network have fixed priorities. For data flow scheduling under different priorities, the links to be released are scheduled in each time slot in descending order of priority. However, when scheduling different data streams under the same priority category, if there is a link transmission conflict, there is a lack of a parameter indicator to determine the scheduling order. Therefore, it is necessary to design a method to provide another priority metric for data flow scheduling under the same priority.

In industrial wireless networks, there is a situation of link conflicts in deterministic scheduling. Link conflicts play a crucial role in data flow and have a significant impact on the network's deterministic scheduling. Moreover, different nodes in the network may experience varying degrees of link conflicts depending on the amount of data flow they pass through. Therefore, considering the potential impact of link conflicts on industrial wireless network data flow during transmission, this paper proposes a scheduling method based on Maximum proportional conflict and deadline first (MPC-D).

The proportion conflict deadline time of data flow F_i in the current time slot t is Δt, and Δt is defined as:

$$\Delta t = \frac{rH_t + c_t}{E_i - t}. \tag{6}$$

In the formula, E_i minus the current time slot t represents the remaining number of time slots for the data stream to complete transmission within the deadline time, rH_t represents the minimum time slot required for the data stream F_i to complete the remaining transmission under the current time slot t, and c_t represents the potential conflict time slot number of the data stream under the current time slot. The calculation method is as follows:

$$c_t = \sum_{q=hop}^{H_i} nf_{hop}. \tag{7}$$

In the formula, *hop* represents the routing location of the current time slot t of the data stream, and nf_{hop} represents the number of neighboring data streams in the *hop* hop.

Given the set of network data streams $F = \{F_1, F_2, \ldots, F_n\}$, the number of available channels m, there are a total of k priority classes in the network, and each data stream has a fixed priority. Within the same priority class, the links to be scheduled arrange channel and slot resources in order of Δt value from large to small. The following rules are used for channel selection: 1) If the first x channels are occupied in the current time slot, the link is arranged in the $x + 1$ *st* channel; 2) If there are no available channels in the current time slot, recalculate the Δt value in the next time slot and reschedule; 3) If the current scheduling link conflicts with the scheduled link in the current slot, scheduling can only be rescheduled according to the Δt value in the next slot. The specific process of the MPC-D scheduling method is shown in Algorithm 1.

Algorithm 1. The process of MPC-D

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Input: $G = (N, V)$, $F = \{F_1, F_2, \ldots, F_n\}$, $F_i(T_i, P_i, E_i, L_i)$, $i \in \{1, 2, \ldots, n\}$, Number of scheduling cycle time slots $T$,
       Available channels $m$
Output: $S[0 \ldots T-1][0 \ldots M-1]$
$t \leftarrow 0$; $c \leftarrow 0$
if $F \neq 0$ then
Sort and categorize according to the fixed priority of the data flow from smallest to largest, $K[] \leftarrow$ Number of
data streams per type
 if the network has passed scheduling preprocessing then
  while $t < T$ do
  for $i \leftarrow 0$; $i < K$; $i{+}{+}$ do
    for $j \leftarrow 0$; $j \leq K[i]$; $j{+}{+}$ do
     if under the current priority, the data flow needs to be scheduled and the link can be scheduled then
      Calculate the values of $\Delta t$ for all currently scheduled links and sort them in descending order
      while $c < M$ do
       $S[t][c] \leftarrow$ the data stream number with the highest $\Delta t$ value
        $c \leftarrow c + 1$
       $S[t][c] \leftarrow$ the data stream number with the highest $\Delta t$ value
        $c \leftarrow c + 1$
      end while
     else
       return the current link is not schedulable
     end if
  end for
  end while
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    else
      return network is not schedulable
    end if
  else
    return error
  end if
```

4 Simulation Process and Result Analysis

The simulation platform operates on a 64-bit Windows 10 operating system. The computer is equipped with a Core i5 processor running at a main frequency of 3.6 GHz and has 16GB of memory. MATLAB is utilized for algorithm programming design. The simulation evaluates the algorithm's performance based on the scheduling success rate and average execution time. The simulation parameters required to describe the network topology are presented in Table 1. In this paper, the proposed MPC-D scheduling method will be compared and analyzed against two classic priority scheduling algorithms: path conflict aware minimum relaxation first (PC-LLF) [14] and conflict aware minimum relaxation first (C-LLF) [15]. When scheduling the network using C-LLF and PC-LLF methods, a conflict looseness is defined for each released link of every data stream in each time slot. Subsequently, the conflicts of the current released link of the data stream and the conflicts of all unscheduled links along the entire transmission path of the data stream are considered separately. This approach aims to achieve a high scheduling success rate with relatively low time complexity.

Table 1. Simulation parameters

Parameter	Definition
n	The number of network nodes
α	The proportion of sources and destination node
ρ	The edge density
m	The number of available channels
β	The upper bound ratio of the relative deadline

Fig. 2 and Fig. 3 illustrates the performance of the three algorithms under varying numbers of nodes. The simulation parameters are set as follows: $n = [10, 20, 30, 40, 50, 60]$, $\alpha = 0.8$, $\rho = 0.6$, $m = 6$, $\beta = 0.8$. Fig. 2 depicts the relationship between the number of nodes and the schedulable ratio for the three scheduling algorithms. It can be observed that the schedulable ratio of MPC-D is similar to that of PC-LLF, indicating that the algorithm can enhance the success rate of network scheduling. Additionally, as the number of nodes increases, the schedulability of all algorithms significantly decreases. This is due to the fact that the number of nodes affects data stream transmission, with more nodes leading to more transmission conflicts.

Fig. 3 presents the relationship between the number of nodes and the average execution time for the three scheduling algorithms. As shown, the average execution time of each algorithm is directly proportional to the number of nodes. Notably, PC-LLF exhibits the highest average execution time. The average execution time of MPC-D is comparable to that of C-LLF and significantly lower than that of PC-LLF.

Fig. 4 and Fig. 5 illustrates the performance of three proposed algorithms for different proportions of source nodes and destination nodes. The simulation parameters are set as follows: $n = 60$, $\alpha = [0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9]$, $\rho = 0.6$, $m = 6$, $\beta = 0.8$. Fig. 4 demonstrates the relationship between the source node and destination node with varying proportions of the three scheduling algorithms and the schedulable ratio. It can be observed that as the proportion of source nodes and destination nodes increases, the schedulability ratio of all scheduling algorithms tends to decline.

Fig. 5 depicts the relationship between the average execution time and the source node and target node in different proportions of the three scheduling algorithms. It is worth noting that as the proportion of source nodes and destination nodes increases, the algorithm's feasibility decreases and the average execution time increases. This is due to the generation of more data flows in the network and subsequent conflicts, leading to scheduling failures.

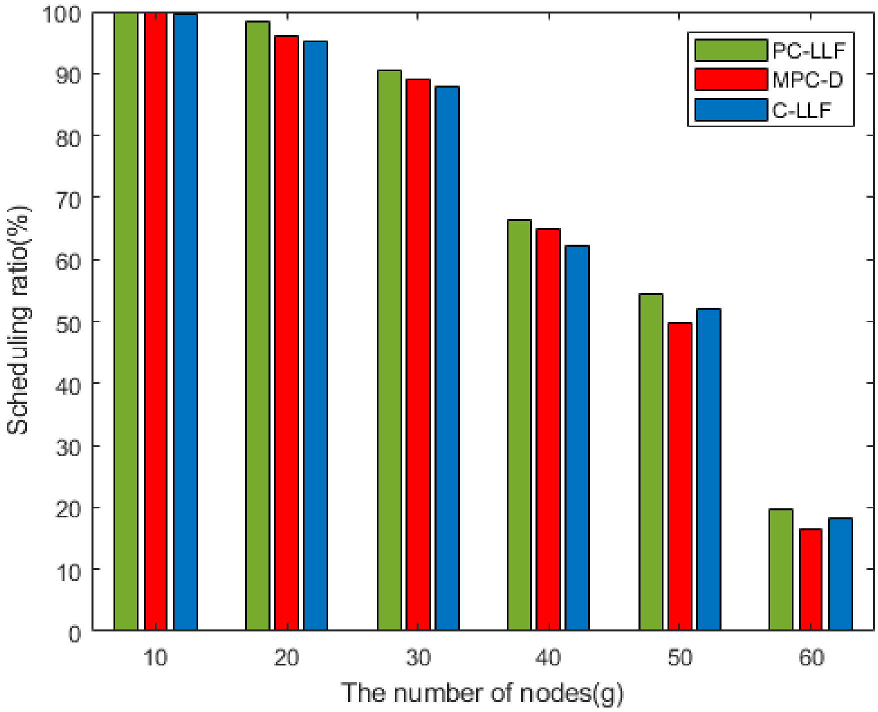

Fig. 2. The performance of the three algorithms under varying numbers of nodes

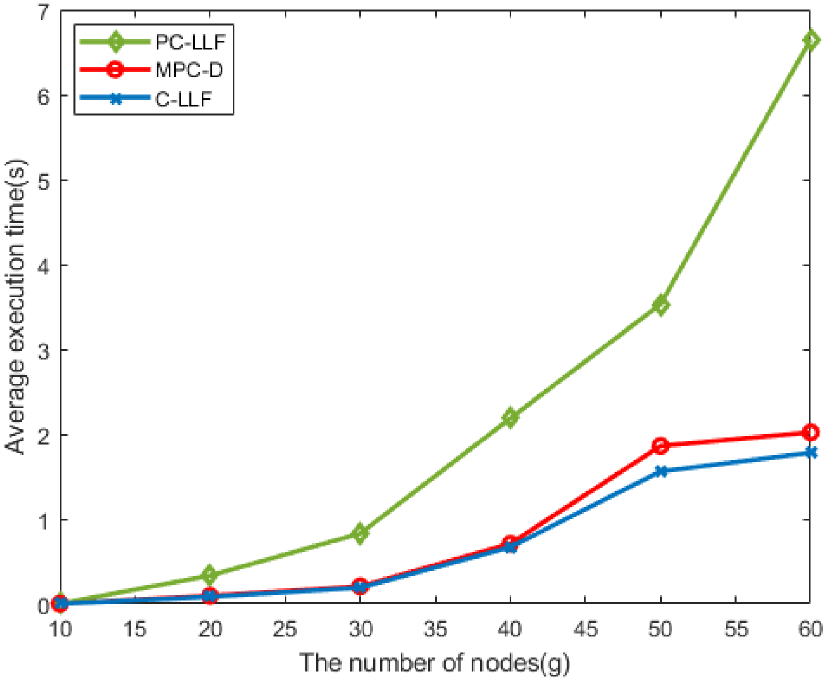

Fig. 3. The performance of the three algorithms under varying numbers of nodes

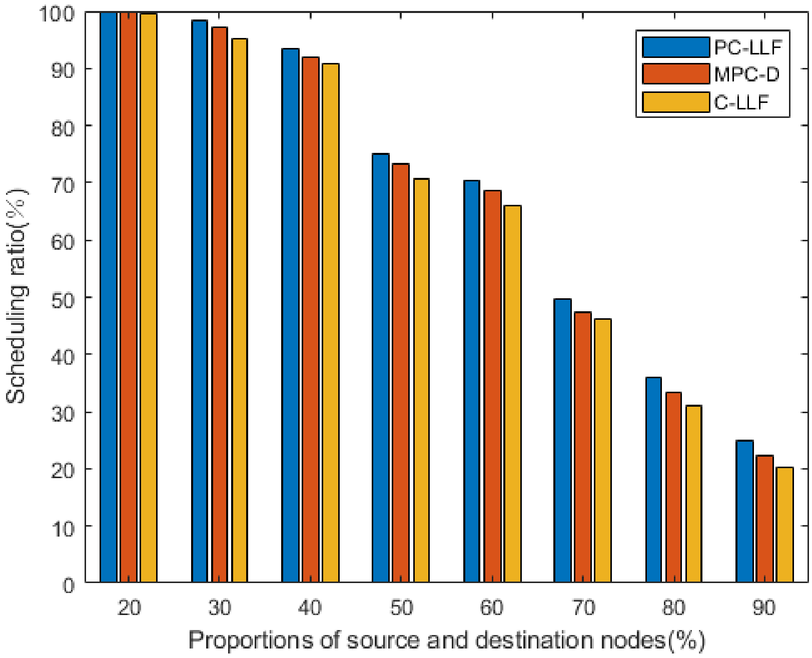

Fig. 4. The performance for different proportions of source and destination node

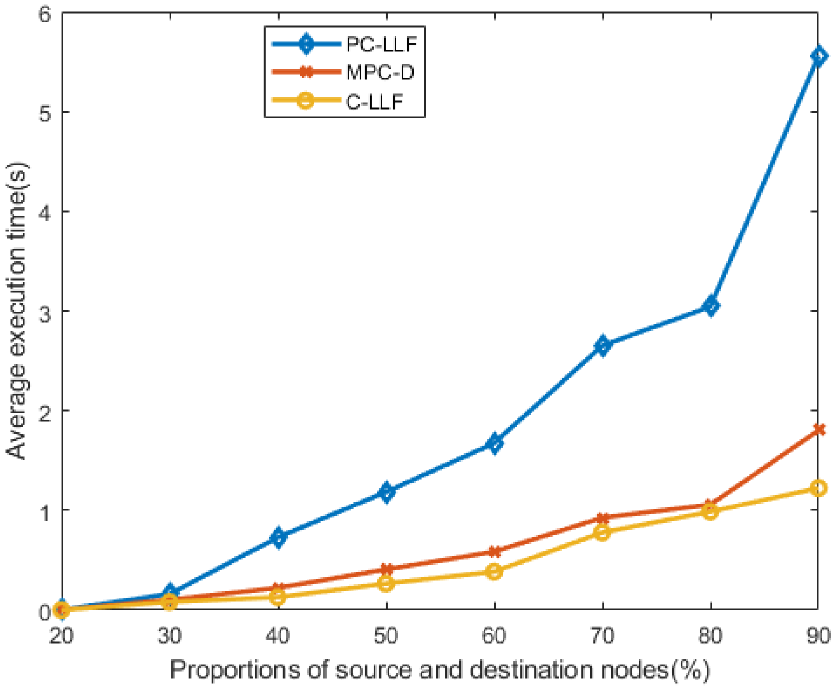

Fig. 5. The performance for different proportions of source and destination node

Fig. 6 and Fig. 7 illustrates the performance comparison of the three scheduling methods under different channel numbers. The simulation parameters are set as follows: $n = 60$, $\alpha = 0.8$, $\rho = 0.6$, $m = [1, 2, 3, 4, 5, 6]$, $\beta = 0.8$. It can be observed that, within a certain range, the scheduling success rate of the three scheduling methods significantly increases with the increase of the number of channels. This is because an increase in the number of channels means that the number of released links that can be scheduled in each time slot also increases, and the additional transmission delay of data flow due to channel competition decreases, thus improving the scheduling success rate of data flow while keeping network data flow constant. However, when the number of channels further increases, although there are more channel resources in each slot, due to the restriction of link conflict, it cannot guarantee that the rich channels will be effectively used, so the scheduling success rate gradually tends to be flat. Additionally, it can be observed that the average execution time of the three scheduling methods first gradually decreases with an increase in the number of channels. When the number of channels increases to 5, the average execution time of the methods remains relatively unchanged.

Fig. 8 and Fig. 9 illustrates the performance comparison of three scheduling methods under different deadline upper limit ratios. The simulation parameters are set as follows: $n = 60$, $\alpha = 0.8$, $\rho = 0.6$, $m = 6$, $\beta = [0.6, 0.7, 0.8, 0.9, 1]$. As shown in Fig. 8, the scheduling success rate of the three scheduling methods gradually increases with the increase of the proportion of the deadline upper limit, and the scheduling success rate of the MPC-D scheduling method is slightly higher than that of the C-LLF scheduling method. This is because a larger deadline leads to more timeslot resources available for data flow transmission in the network, increasing the likelihood of data flow reaching the destination node within the required deadline. Additionally, we observe that the average execution time of the three scheduling methods increases with the increase of the deadline, as more time slots for data stream transmission in the network lead to an increase in the average execution time of the scheduling method. When scheduling an industrial wireless network, an appropriate cut-off time upper limit proportion should be selected to balance the scheduling success rate and the execution time of the scheduling method.

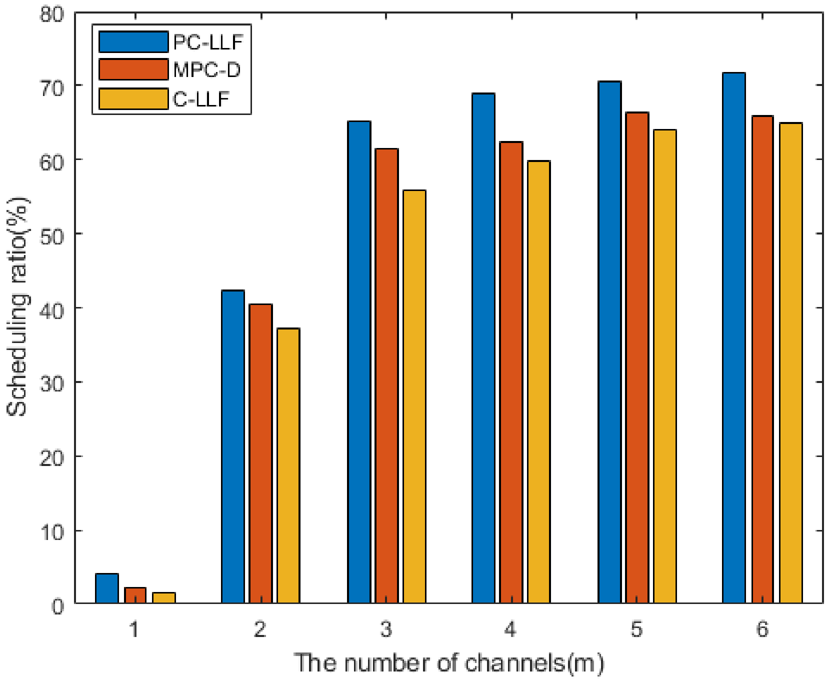

Fig. 6. The performance of the three algorithms under different channel numbers

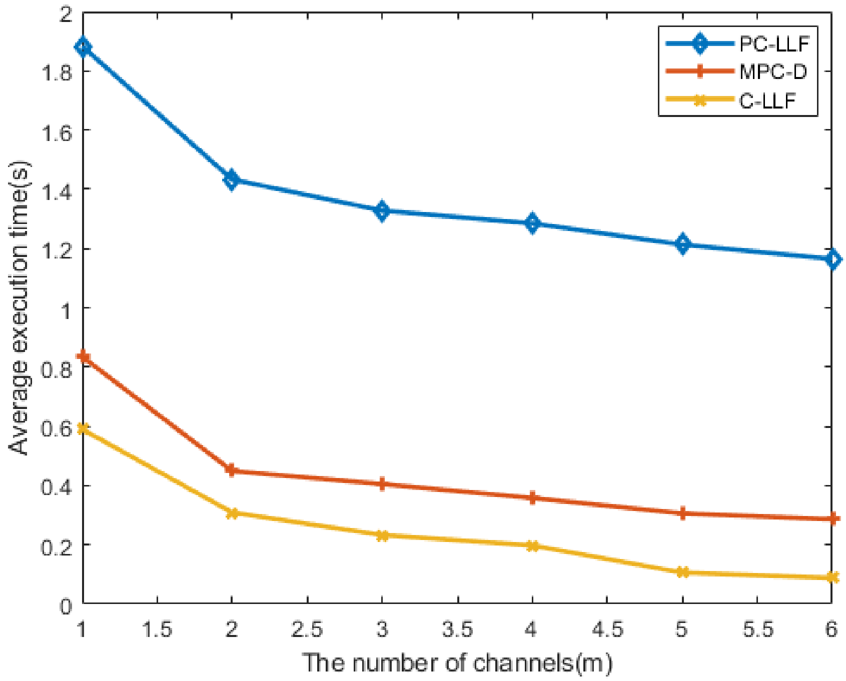

Fig. 7. The performance of the three algorithms under different channel numbers

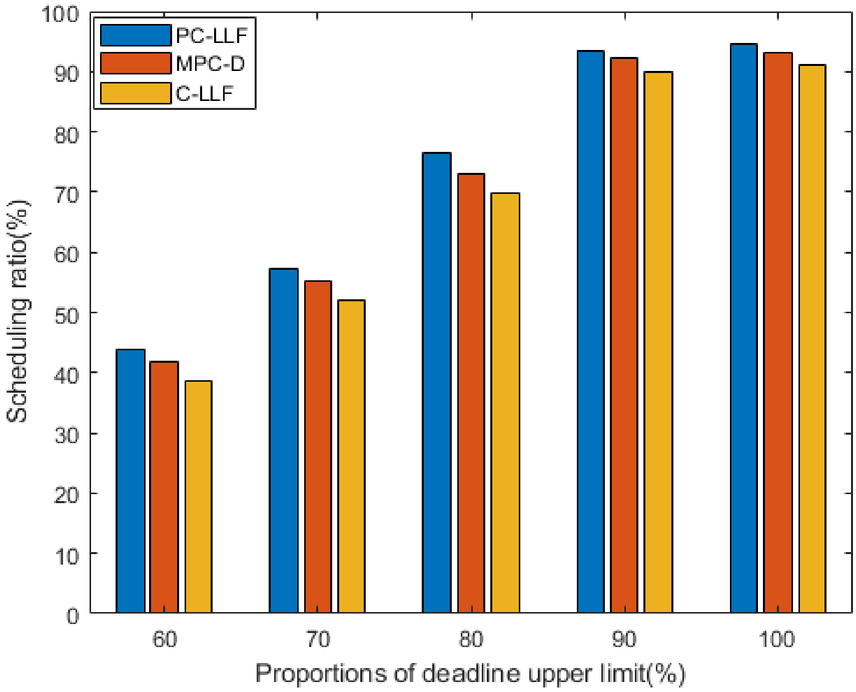

Fig. 8. The performance of the three algorithms under different deadline upper limit ratios

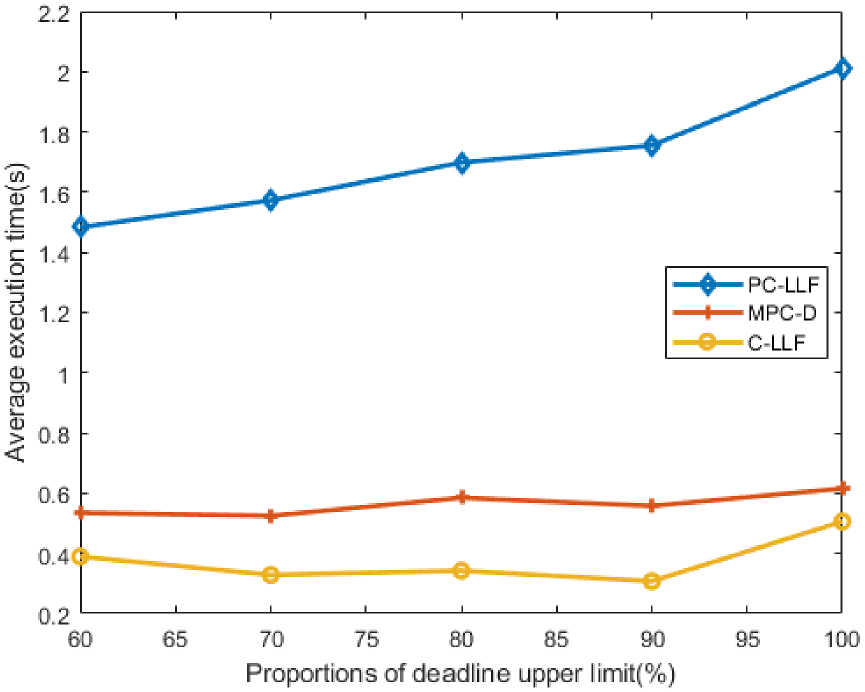

Fig. 9. The performance of the three algorithms under different deadline upper limit ratios

5 Conclusion

This article investigates the deterministic scheduling problem of data streams based on priority classification in industrial wireless networks. Based on the mathematical description of the data stream model, two factors that cause transmission delay in low-priority data streams are analyzed: link conflict and channel competition. Based on the analysis results of data flow delay, schedule and preprocess the network data flow to eliminate some networks with unreasonable parameters, and provide feedback to the network manager. A dynamic MPC-D scheduling algorithm based on Maximum proportional conflict and deadline first is proposed for potentially containing multiple data streams under the same priority. Simulation results show that compared to classical algorithms, MPC-D algorithm can achieve higher success rate of scheduling solution and lower algorithm time execution. The drawback is that when the network size is large, the computational efficiency and scheduling success rate decrease significantly. In the future, further optimization research will be conducted on the performance of the MPC-D algorithm in large-scale networks. In addition, this article adopts a randomly generated network approach for simulation, which can be further combined with representative process control application scenarios for simulation analysis in the future. A physical network can be built and tested and verified in a real industrial environment to further improve the practicality of the scheduling algorithm.

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